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Metallographic Analysis of Brush Bristle and Integrity Testing of Brush Seal in Shroud Ring of T–700 Engine

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ABSTRACT

Post-test investigation of a T–700 engine brush seal found regions void of bristles ("yanked out"), regions of bent-over bristles near the inlet, some "snapped" bristles near the fence, and a more uniform "smeared" bristle interface between the first and last axial rows of bristles. Several bristles were cut from the brush seal, wax mounted, polished, and analyzed. Metallographic analysis of the bristles near the rub tip showed tungsten-rich phases uniformly distributed throughout the bristle with no apparent change within 1 to 2 μm of the interface except for possibly a small amount of titanium, which would represent a transfer from the rotor. Analysis of the bristle wear face showed nonuniform tungsten, which is indicative of material resolidification. The cut end contained oxides and internal fractures; the worn end was covered with oxide scale. Material losses due to wear and elastoplastic deformation within the shear zone and third-body lubrication effects in the contact zone are discussed.

INTRODUCTION

The preliminary results of brush seal testing have been reported in Hendricks et al. (1993). The post-test metallographic work on that same seal is described herein. The split-ring brush seal was fabricated, installed between two labyrinth-honeycomb shroud seals, and tested in the fourth-stage turbine of a T–700 engine (Fig. 1; Hendricks et al., 1993).

Brush Seal Geometry

The brush seal was made up of 0.0028-in. (0.071-mm) diameter Haynes 25 bristles angled 43° to 50° to the interface with about 2500 per inch of circumference (98.4 per millimeter

of circumference) (Fig. 2; Hendricks et al., 1993). The backing washer was angled 19° to match the slope of the turbine shroud. The design clearance was -0.02 in. (-0.51 mm) but could range to -0.05 in. (-1.27 mm) diametral (the uncertainty reflecting that of the engine geometry) with an outside diameter of 13.146 in. (333.9 mm) and an inside diameter of 12.690 in. (322.3 mm).

Operating Conditions and Interface Geometry

The annealed Haynes 25 bristles rubbed directly against the nonconditioned, irregular René 80 turbine blade shroud surface. Turbine speeds were 10 000 and 20 000 rpm, and average fourth-stage turbine shroud temperatures were 850 and 1050 °F (455 and 566 °C), respectively. The turbine inlet temperatures were about 250 deg F (139 deg C) higher.

The turbine assembly has 50 shrouded blades with irregularities (radial, to 0.009 in. (0.023 mm); circumferential, to 0.003 in. (0.076 mm); and axial, to 0.002 in. (0.0051 mm)) representing protrusions into the brush and the spaces between the blade pairs. It is not known how many cycles were required to "free the bristles," but at 10 000 rpm and with 50 irregular asperities impacting each bristle (4000 impacts/s at a surface speed of 550 ft/s (168 m/s)), it is assumed that brush break-in was rapid.

A total of 21 hr of cyclic and steady-state data were taken. Wear appeared to be rapid initially, with an orange flash of hot brush fragments during the first engine startup, but decreased to none in less than 10 hr of operation.

Tribological Pairing

Derby and England (1992) reported minimal brush and coating wear using an Alloy A bristle with Triboglide coating. Alloy A (a solid-solution-strengthened, nickel-chromium-aluminum-based superalloy) is being used in gas turbine hot spots and develops a tenacious chromia (Cr_2O_3) and alumina (Al_2O_3), yttria-modified oxide layer. Triboglide is a chromium carbide (CrC) containing a total of 12 wt % barium and calcium fluoride solid lubricants. Triboglide is based on the work of Harold Sliney at NASA Lewis Research Center but has no silver additive. The tests were performed with 1200 °F (650 °C) air.

Atkinson and Bristol (1992) reported less wear for a cobalt-based alloy rubbing against CrC at room temperature than for a nickel-based alloy but nearly equivalent wear for either alloy at 480 °C (900 °F). However, the cobalt alloy/CrC combination proved to leak less under dynamic conditions and wear less at room temperature. The tests were conducted to simulate a CT7–9 compressor discharge seal. The brush was 5.08 in. (129 mm) in diameter and of standard Cross Mfg. construction.

Metallographic results of a T–700 engine test (Hendricks, et al., 1993) illustrated some material migration along the bristle and material transfer both from and to the rotor surface (Fig. 3; Hendricks et al., 1993). Material smears seem to be in line with the softer brush material rubbing a harder material; the sacrificial bristles appeared to be oxidized, pitted, and rubbed by line-to-line contact. It is not clear how the irregularities of the interface affected these results, but it is clear that materials were transferred and that they probably melted upon initial rub-in due to the high interface temperature.

Tribological pairing is important and Hendricks et al. (1993), Derby and England (1992), and Atkinson and Bristol (1992) provide an initial look at the problem. This paper gives further details of the results of the engine test of a brush seal described in Hendricks et al. (1993).

ANALYSIS AND DISCUSSION

Several bristles (wires) of the brush seal tested in a T–700 engine (Hendricks et al., 1993) were cut, wax mounted, polished, and analyzed. The bristles and sections were mounted in a low-melting-point wax, rough lapped with 3-μm diamond grit, polished with 1-μm diamond grit, and coated with palladium for light optic and scanning electron microscope viewing.

Bristles Cut From Brush Seal

Bristle tip irregularities caused by the rub interface (Fig. 4) indicate some form of material transfer and material smearing. However, metallographic analysis of the bristle near the rub tip showed tungsten-rich phases distributed throughout the bristle with no apparent change within 1 to 2 μm of the interface. From the Blok problem (Carslaw and Jager, 1959) the temperature was sufficient to melt the bristle, but the materials may fail in shear before melting (like pulling a taffy), form oxides and pits, transfer to the interface or form layers less than 1 μm thick, wear away, or all of the preceding.

Figure 5 illustrates a wear surface, although the angle does not always represent a wear surface. From 2 μm to several millimeters from the interface, there appears to be no change in tungsten composition. Green dots are near the edge (micrometer range) and red is away from edge (millimeter range), showing little or no change in tungsten distribution, but the surface appears to be coated (oxides are discussed later).

A more detailed analysis was conducted on bristles also cut from the post-test brush seal. Micrographs of the cut end and the rubbed (worn) end are shown in Fig. 6 and the associated element spectra in Figs. 7 and 8, respectively. Figures 6 and 7 show oxides and internal fractures in the cut end. Figures 6 and 8 show that the worn end is covered with a scale that looks like oxide scale at 5000X. The oxygen level from the cut to worn ends increased from 5.7 to 12.7 percent; the cobalt level decreased from 32.5 to 22.0 percent; and the chromium level dropped from 24.4 to 22.3 percent. Formation, rubbing (flaking), and reformation of oxide scale can provide a third-body lubrication effect.

The bristle element spectra are dominated by cobalt, chromium, and tungsten lines representative of a cobalt-based alloy such as Haynes 25 (see Table 1). Most spectra show oxide scale and little material transfer from the René 80 rotor (Table 1) to the bristle. However, increases in nickel and molybdenum (Fig. 9) illustrate that material transfer from the rotor to the bristle tips did occur. Nevertheless, scrapings from the René 80 rotor-bristle wear track (Fig. 10; see also Fig. 3) were rich in cobalt, which is characteristic of Haynes 25 transfer to the rotor, with a little evidence of titanium, which is indicative of transfer from the rotor to the bristle tip. Therefore, the sacrificial elements were the Haynes 25 bristles, as designed.

TABLE 1.—COMPOSITION OF RENÉ 80 AND HAYNES 25

Composition, wt %	
René 80	Haynes 25
60 Ni[a]	50 Co[a]
14 Cr	20 Cr
4 W	15 W
9.5 Co	10 Ni
4 Mo	3 Fe
3 Al	1.5 Mn
5 Ti	0.1 C
0.17 C	
0.015 B	
0.03 Zr	

[a]Balance.

With significant material transfer to the rotor and oxide scale formation over the bristle surface indicated by Figs. 9 and 10, an examination of a bristle tip (Fig. 11) showed wear traces, pitting, and material transfer. Figure 12 illustrates that although the base material appears as Haynes 25, the distribution of tungsten differs as noted in the element spectra. Therefore, some form of resolidification must have occurred right at the bristle–rub runner interface.

Note that these tests were conducted in the fourth stage of a shrouded turbine disk where the fluids to be sealed were combustion gases, with cooling air to 1200 °F (650 °C). The principal elements of such gases are oxygen, steam, carbon dioxide, and nitrogen. In the tests conducted at GE (Atkinson and Bristol, 1992) and at EG&G (Derby and England, 1992) the working fluid was probably air (0.8 N_2 and 0.2 O_2 approx.) at temperatures to 1200 °F (650 °C) (equivalent to our shroud temperatures) at EG&G and 480 °C (895 °F) at GE. Both are above the transition temperature for cobalt (Derby and England, 1992). Also, note that the T–700 engine was probably fuel rich on startup and lean on shutdown so that oxide scaling could occur by engine air cooling of the heated bristles and by steam corrosion. The GE tests were for 100 hr, the EG&G tests for 1.5 hr, and the T–700 test for 30 hr.

Brush Seal Configuration

The post-test brush seal was examined by using a micro-video system. Several irregularities associated with installation were noted. One region was void of bristles; perhaps they were yanked out (Fig. 13(a)). Adjacent bristles were all bent over, on the leading edge but not in the core (Fig. 13(b)). One bristle of original length was kinked at the tip and appeared to be approximately 2.5 times as long as the remaining bristles (Fig. 13(c)). A closer look revealed some "snapped" bristles in that region, perhaps from forcing the brush into position or from catching bristles within the turbine blade gaps (Fig. 13(d)). The snapped bristles were very close to the pinch washer. Bristles near the pinch washer were broken or bent, but deeper into the brush bristle pack (N_x) the bristles were straight and worn (Fig. 13(e)). The appearance of the first three rows N_x of the brush showed erratic rubbed wires, probably due to installation deformations. For $N_x > 3$ the appearance was more uniform for the next nine rows. Higher magnification of the interface showed "smearing" of the bristle tips (Fig. 13(f)). Each bristle appeared to have some scale covering it, as evidenced from wire highlights and differential coloring, like air-quenched steel (Fig. 13(g)).

Other effects of the rubbing interface are discussed in Hendricks et al. (1992–93).

CONCLUSIONS

Post-test evaluation of the brush bristles and brush sections cut from the brush shroud seal run in the fourth-stage shrouded turbine disk of a T–700 engine provided the following information.

Cut Bristles

1. Bristles cut from the brush showed little or no evidence of tungsten redistribution, indicating that little or no resolidification had occurred over the bristle length.
2. Bristles exhibited surface oxidation, pitting, color differentials, and scaling over their lengths with significant oxidation at the rub interface. Bristle tips were irregular in shape.
3. Rotor scrapings showed material transfer from the Haynes 25 brush to the René 80 rotor. The brush was sacrificial, as designed.
4. The bristle tips showed irregular distribution of tungsten, which is indicative of resolidification in a very thin layer at the rubbing interface.

Seal Configuration

5. "Blind" installations and forcing the brush onto segmented rotors can lead to distortion of the first few and last bristle rows and to local pullout.
6. Bristle tip smearing at the rub interface was commonplace, with the appearance of mudflat cracking but with a uniform wear track.
7. The mechanical aspects of the brush survived the harsh test environment.

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Hendricks, R.C., Carlile, J.A., and Liang, A.D., 1992, "Brush Seal Bristle Flexure and Hard Rub Characteristics," NASA TM–105864.

Hendricks, R.C., Griffin, T.A., Bobula, G.A., Bill, R.C., and Howe, H.W., 1993, "Integrity Testing of Brush Seal in Shroud Ring of T–700 Engine," ASME Paper 93–GT–373. (Also, NASA TM–105863.)

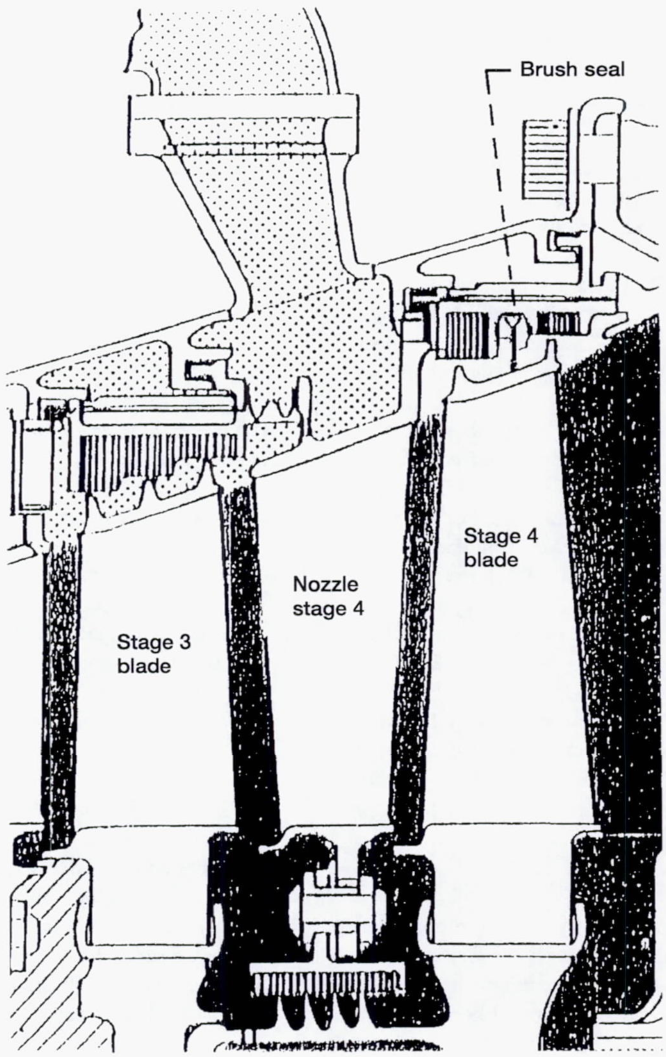


Figure 1.—Schematic of power turbine. From reference 1.

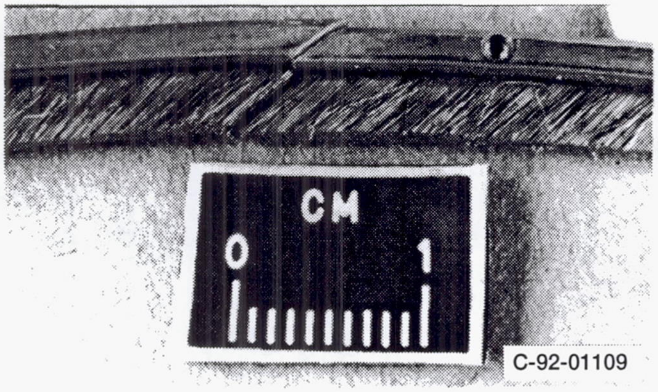
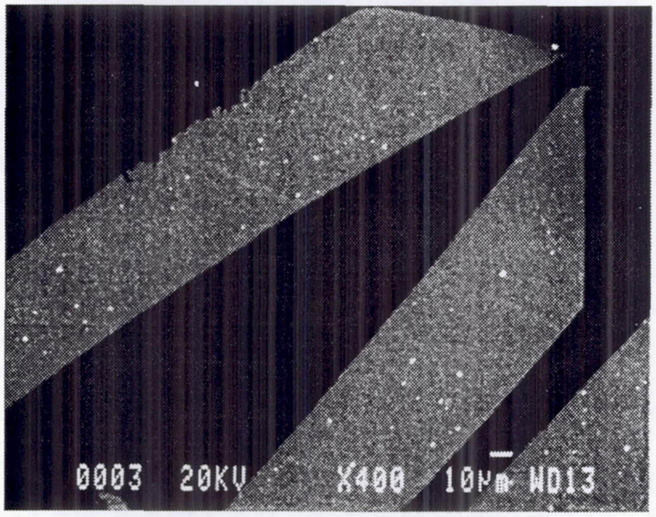


Figure 2.—Split-ring brush seal. From reference 1.



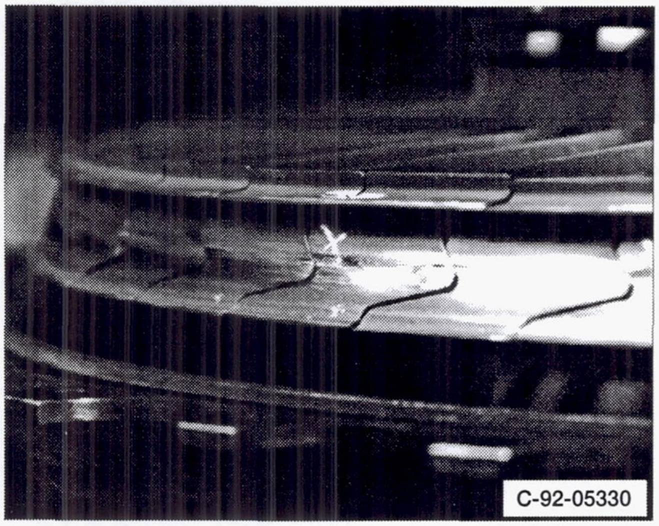


Figure 3.—Fourth-stage turbine after testing, showing polishing of leading edges.

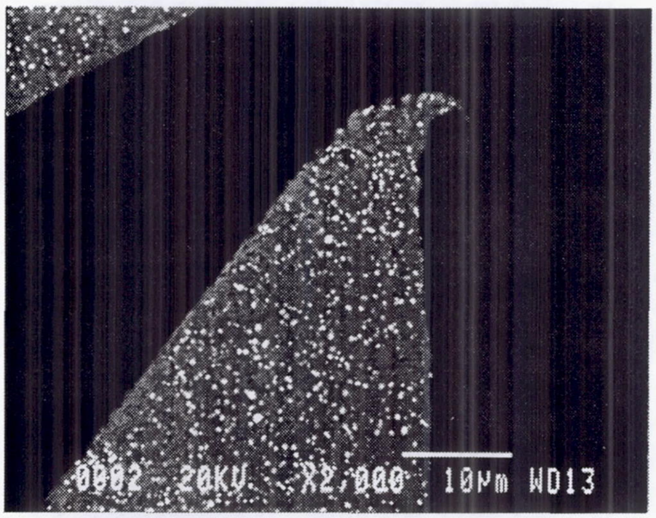


Figure 4.—Post-test analysis of bristles cut from brush seal, showing irregular tips.

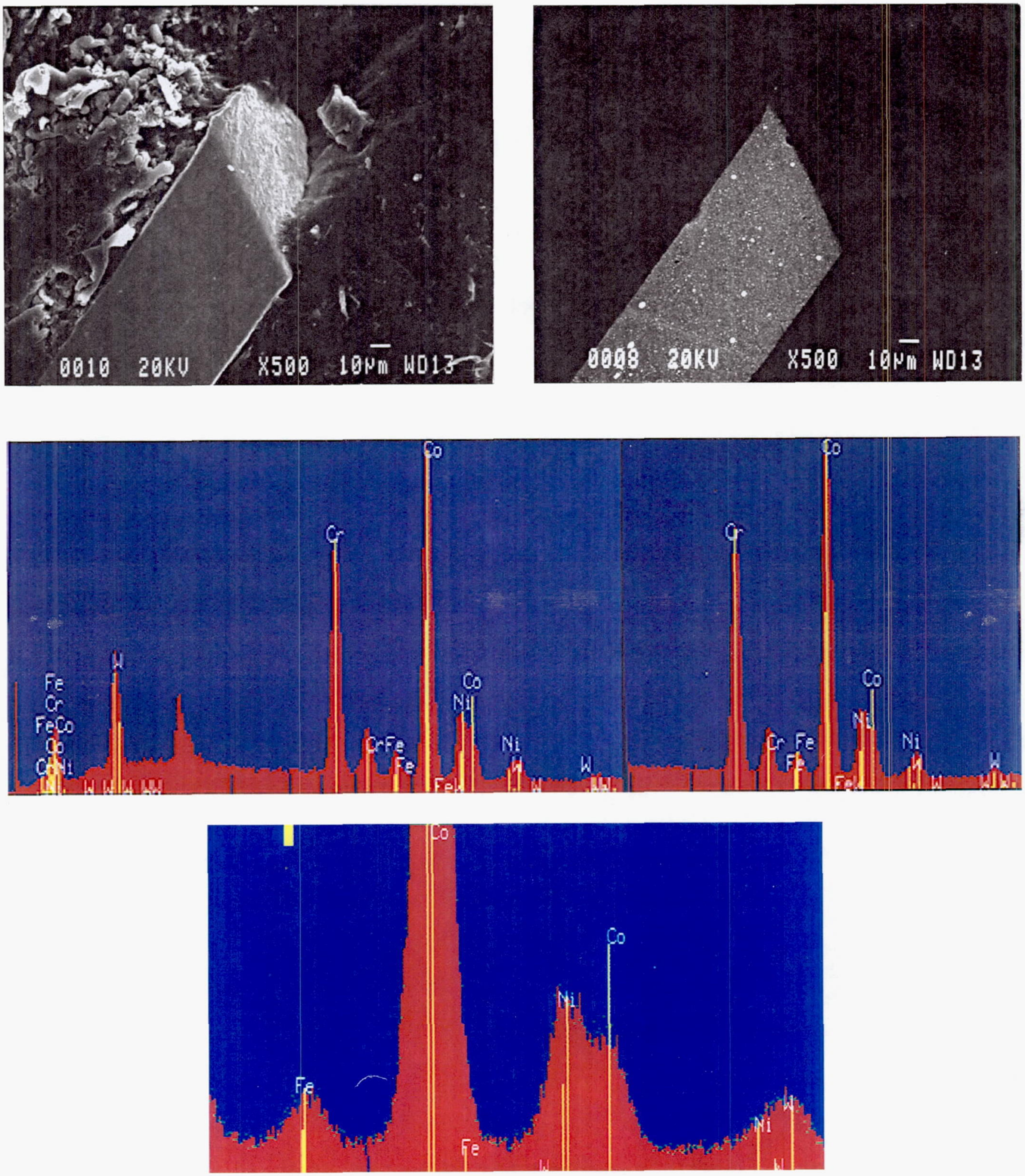
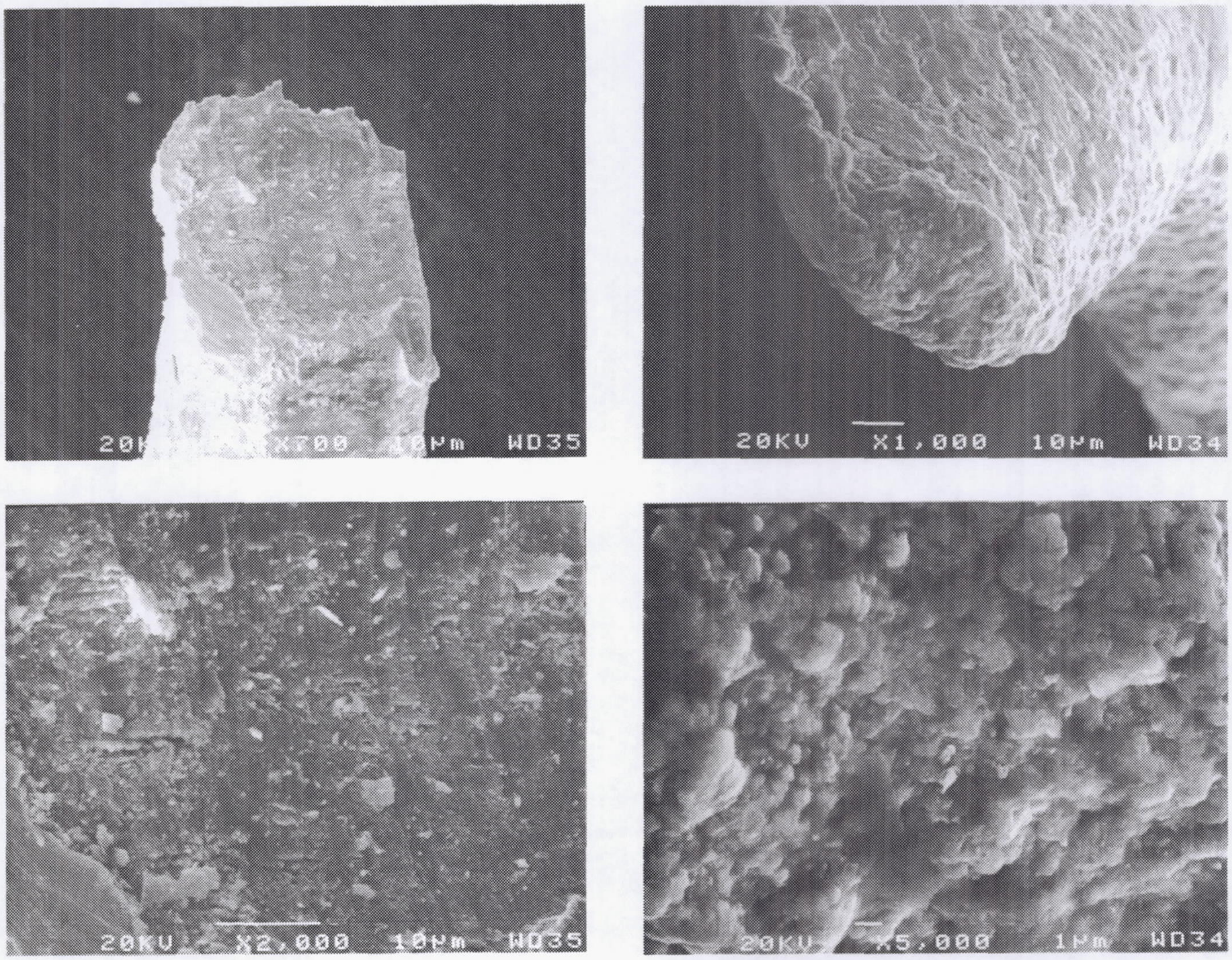


Figure 5.—Wear surface and oxidation with element compositon.



(a) Cut end.

(b) Worn end, showing oxide formation.

Figure 6.—Bristle cut and worn ends.

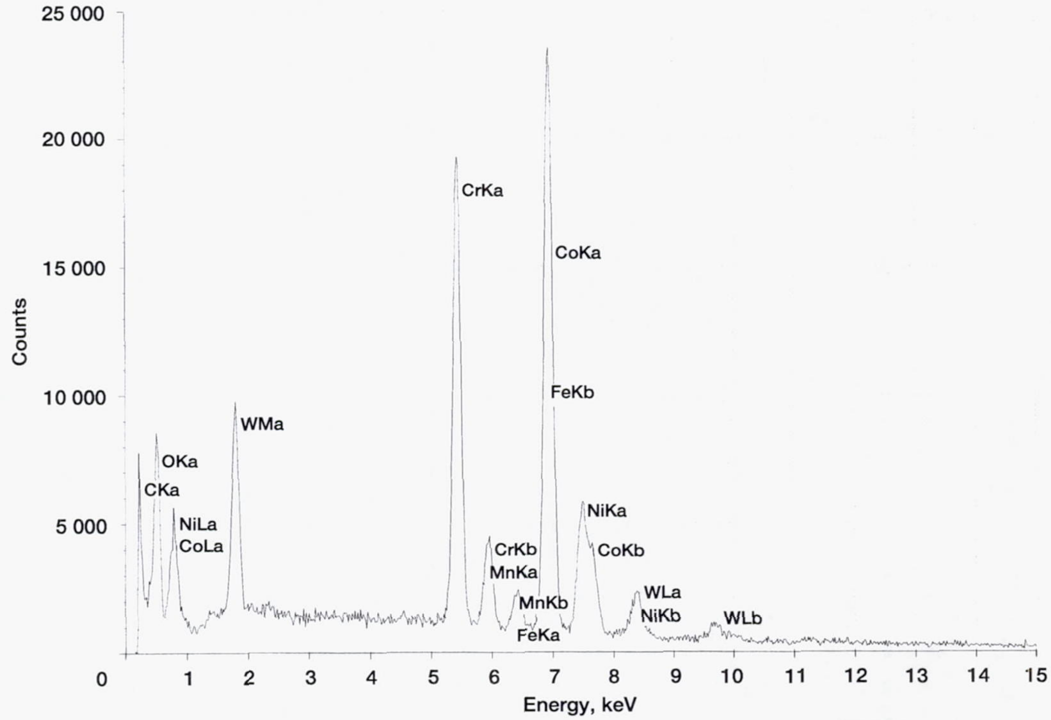


Figure 7.—Composition of bristle cut ends. Spectrum B091592: beam current, 0.3 nA; count time, 200 s; accelerating potential, 20 kV; beam spot magnification, 2000.

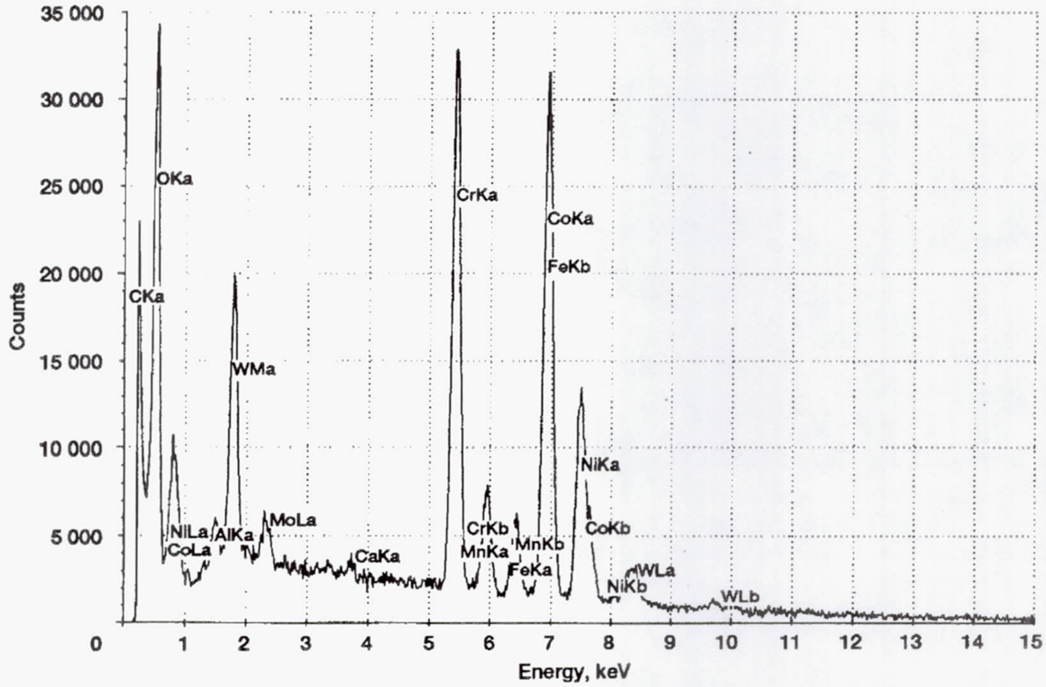


Figure 8.—Composition of bristle worn ends. Spectrum B091592: beam current, 0.3 nA; count time, 200s; accelerating potential, 20 kV; beam spot magnification, 5000.

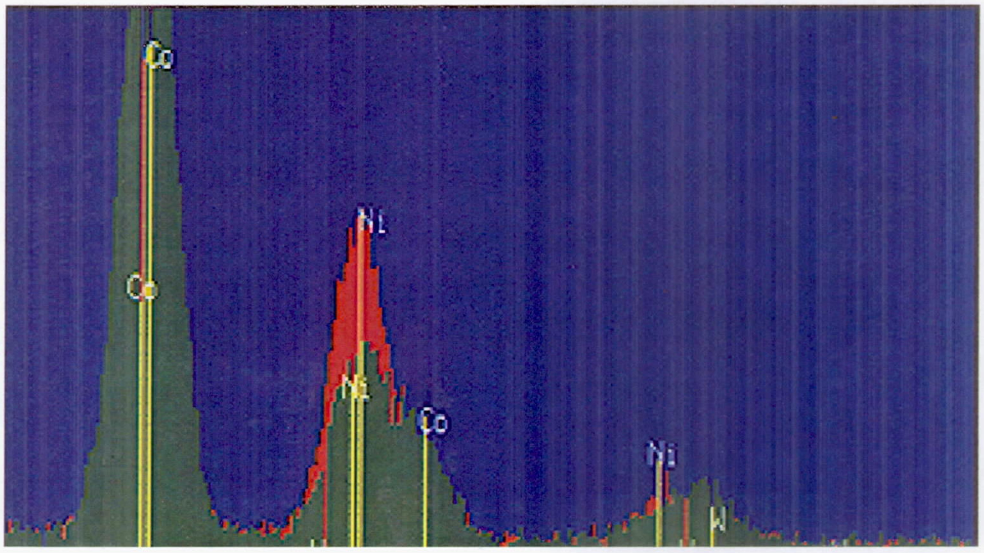


Figure 9.—Material transfer from René 80 rotor to Haynes 25 bristle.

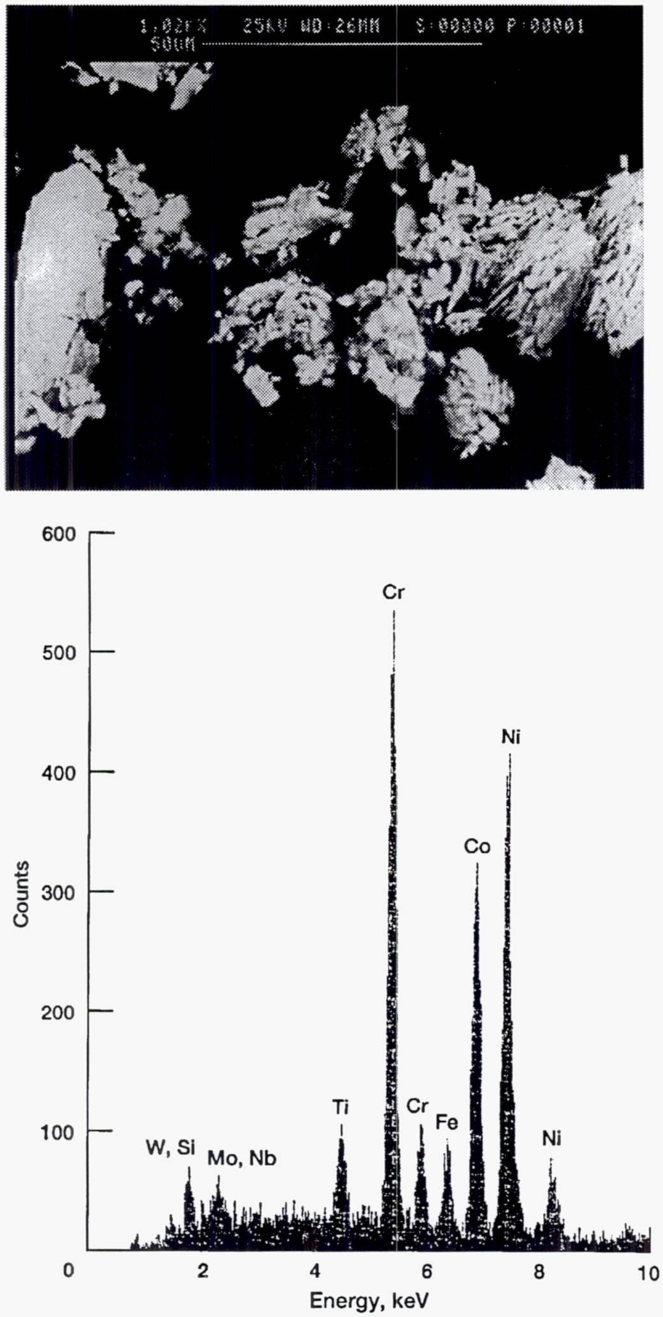


Figure 10.—Typical element spectra of post-test material scraped from René 80 rotor-particle WS1A.

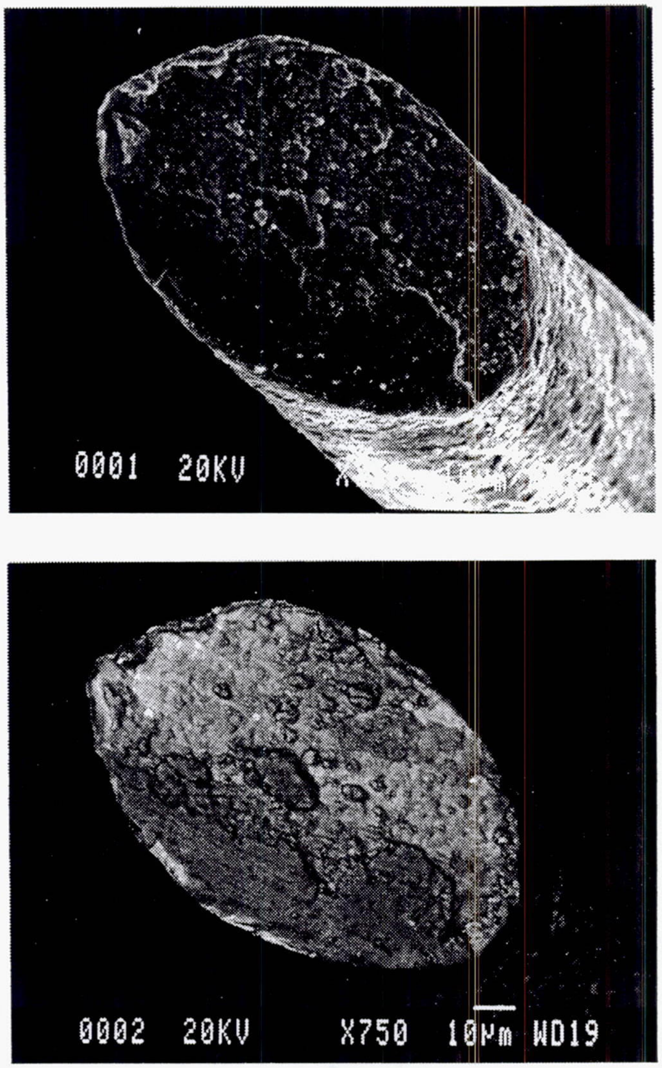
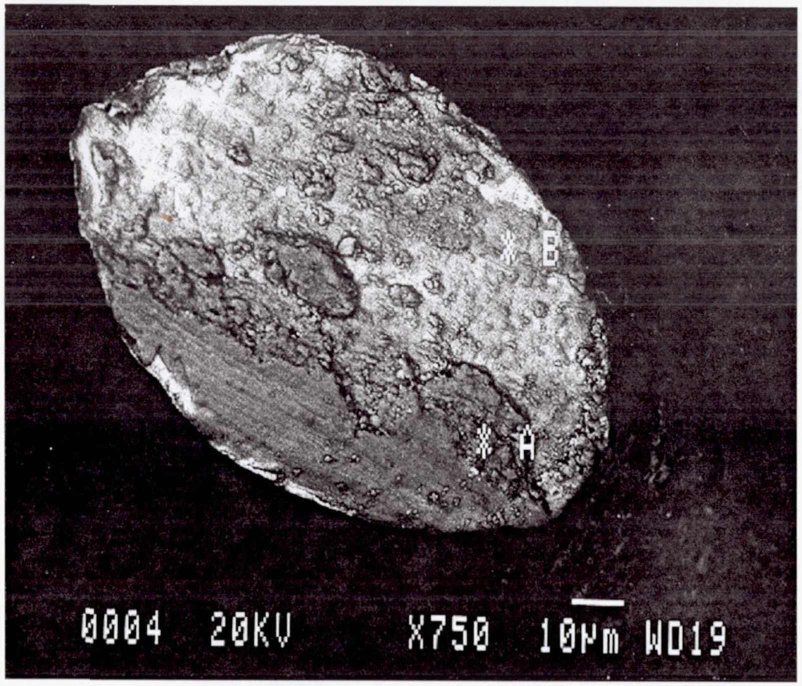
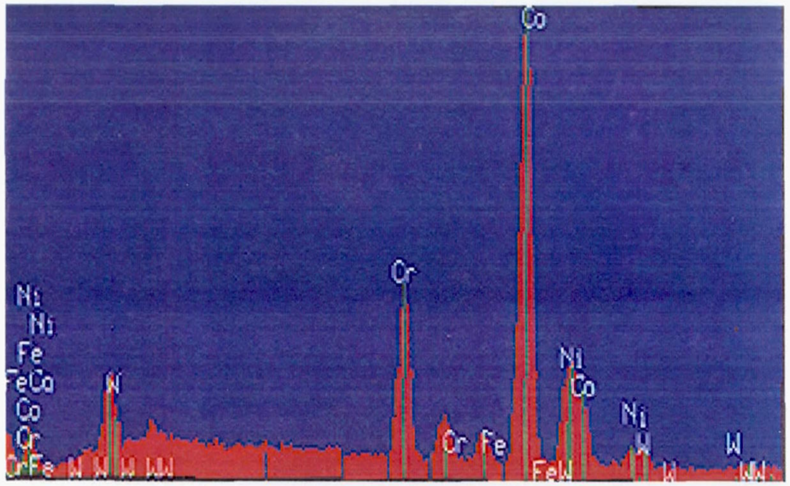


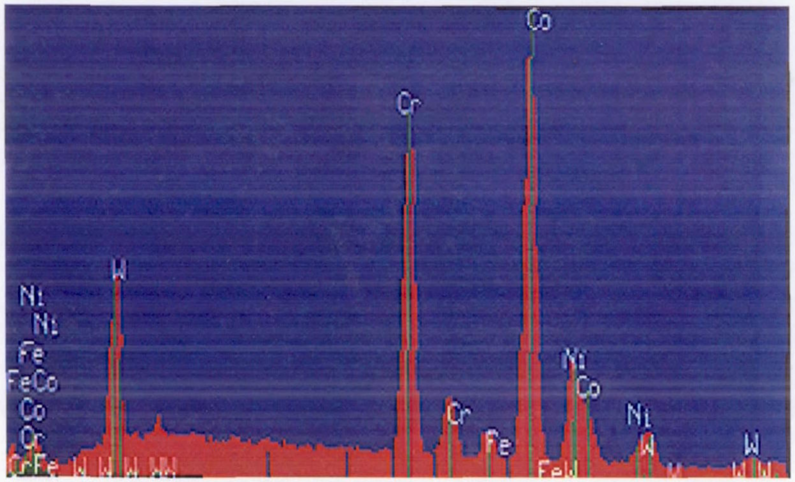
Figure 11.—Material transfer at bristle tip.



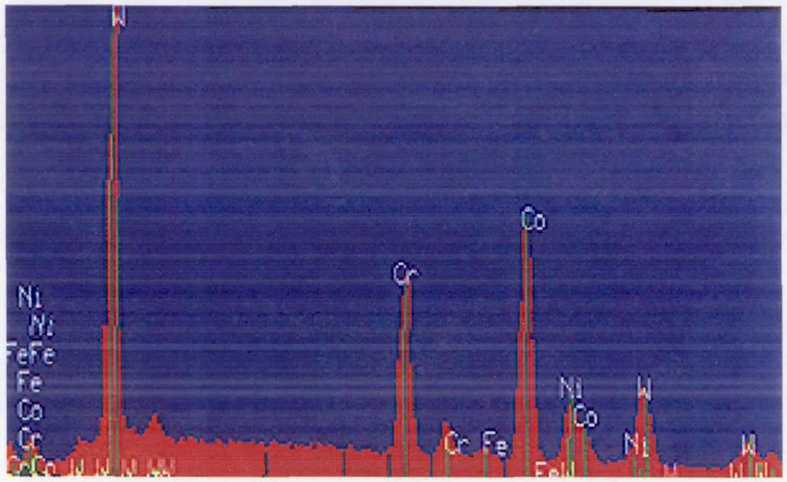
(a) Spectra locations A, B, and C.



(b) Spectra location A.

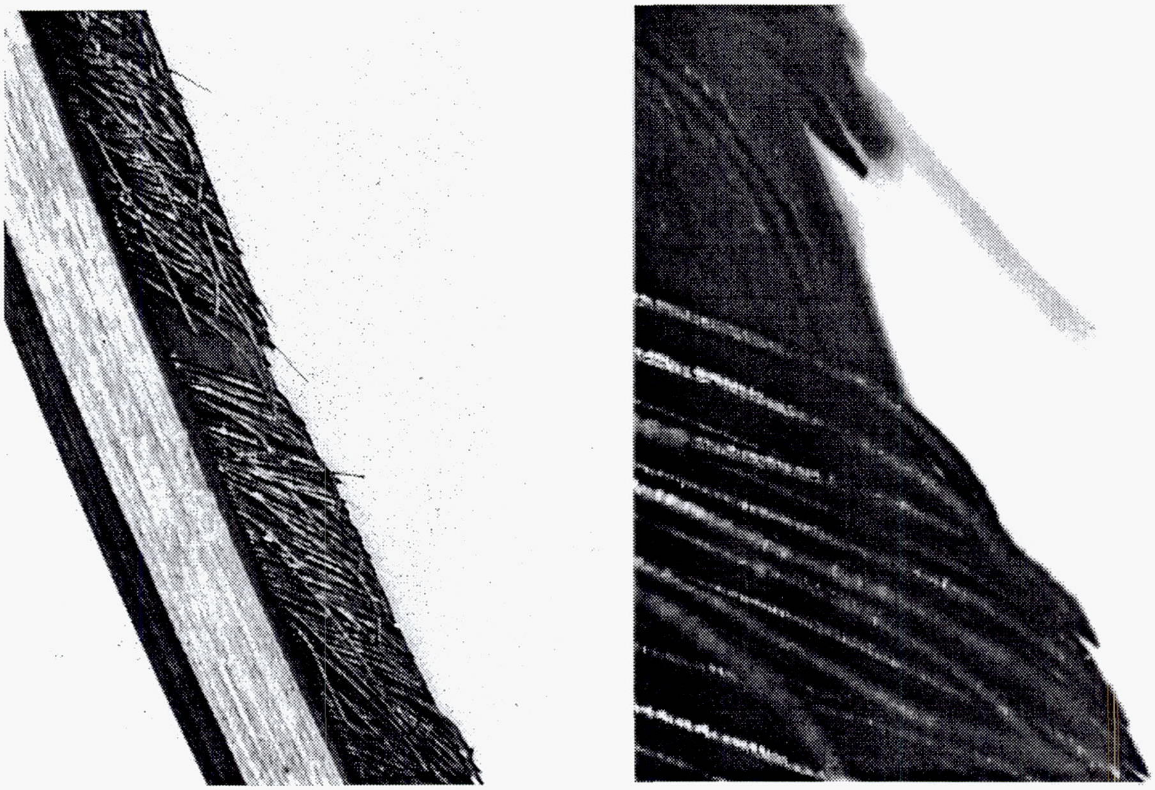


(c) Spectra location B.

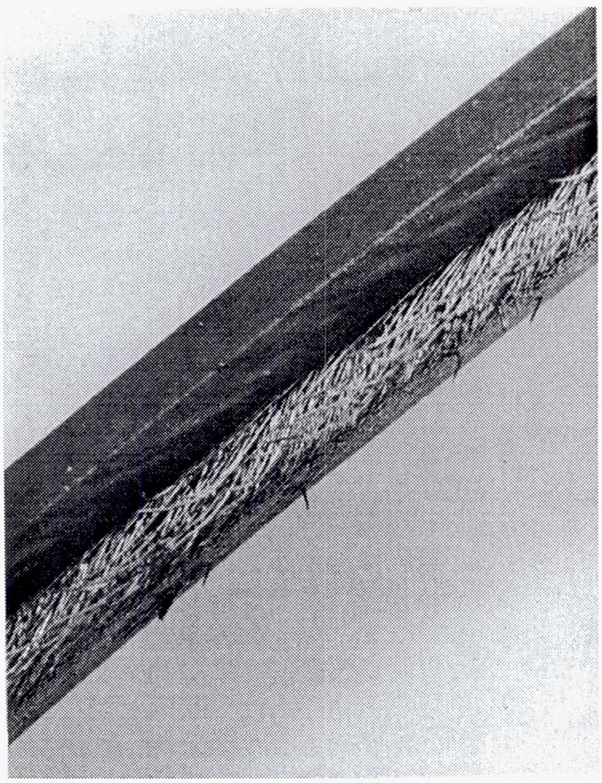


(d) Spectra location C.

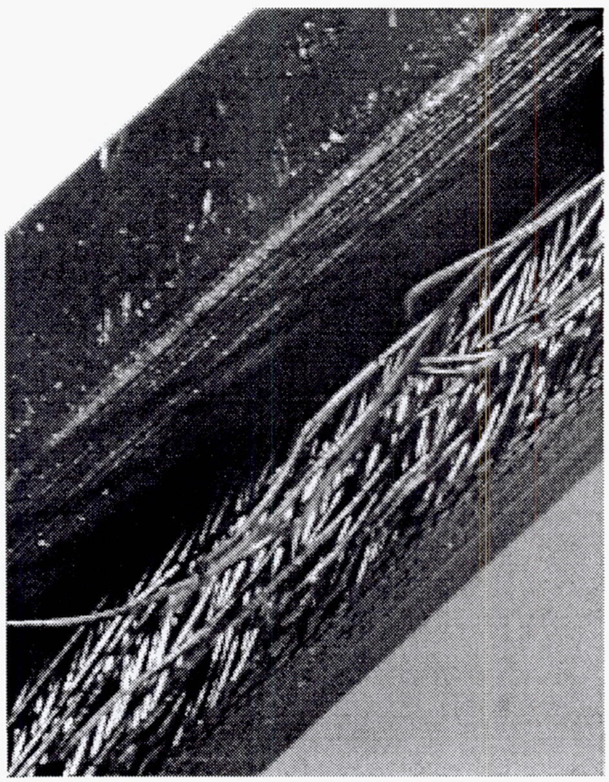
Figure 12.—Tungsten variations over bristle tip.



(a) Region void of bristles.

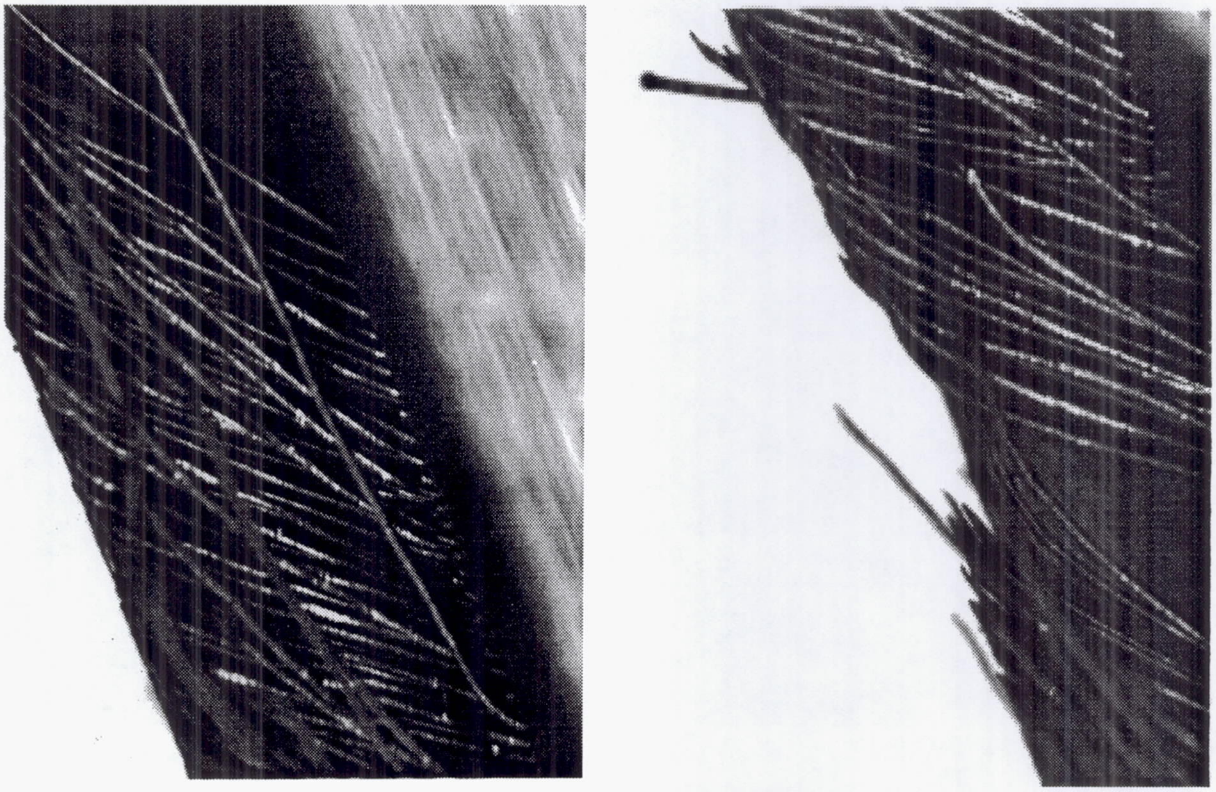


(b) Bristles bent over (on leading edge but not in core).

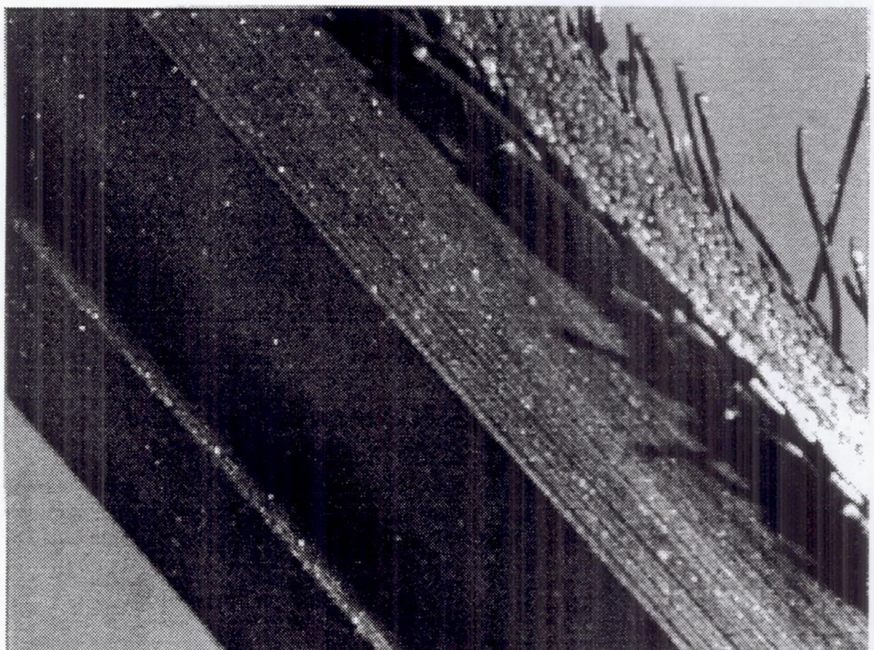


(c) Bristles kinked at tips; appear about 2.5 times as long as remaining bristles.

Figure 13.—Bristle geometry associated with installation, noted in post-test evaluation.

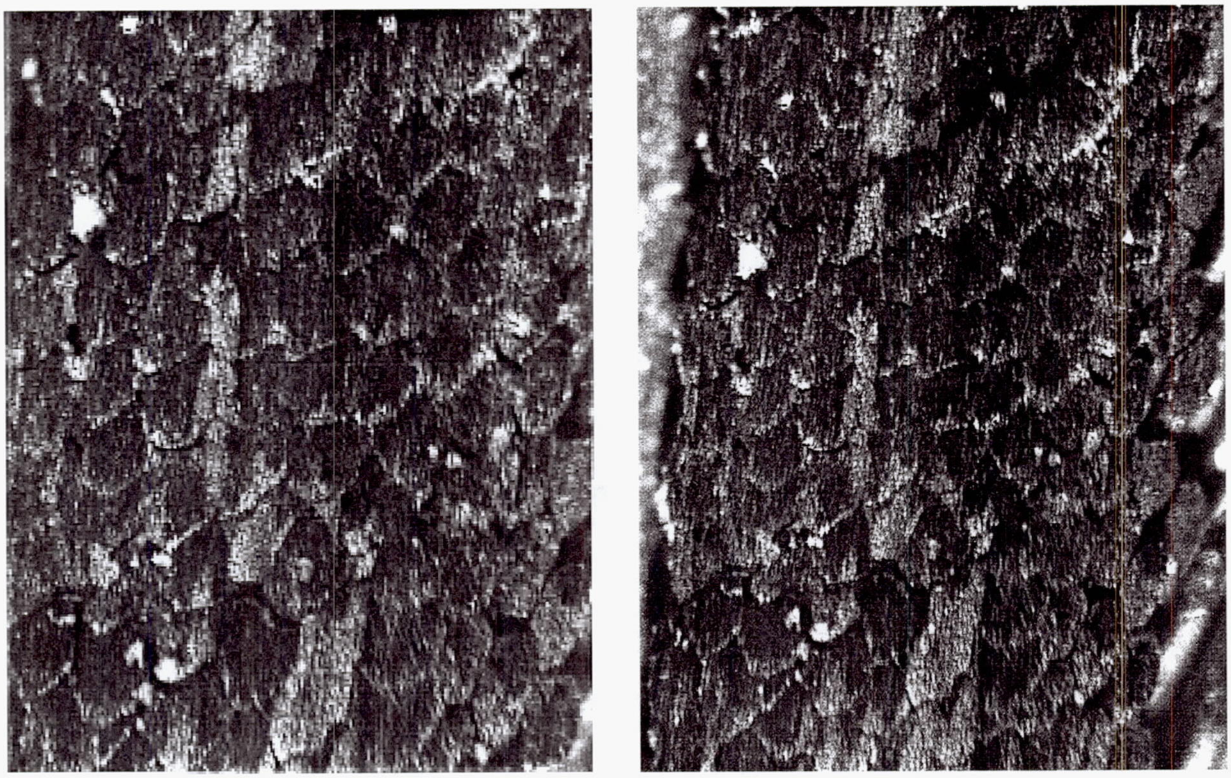


(d) Bristles caught within turbine blade gaps.

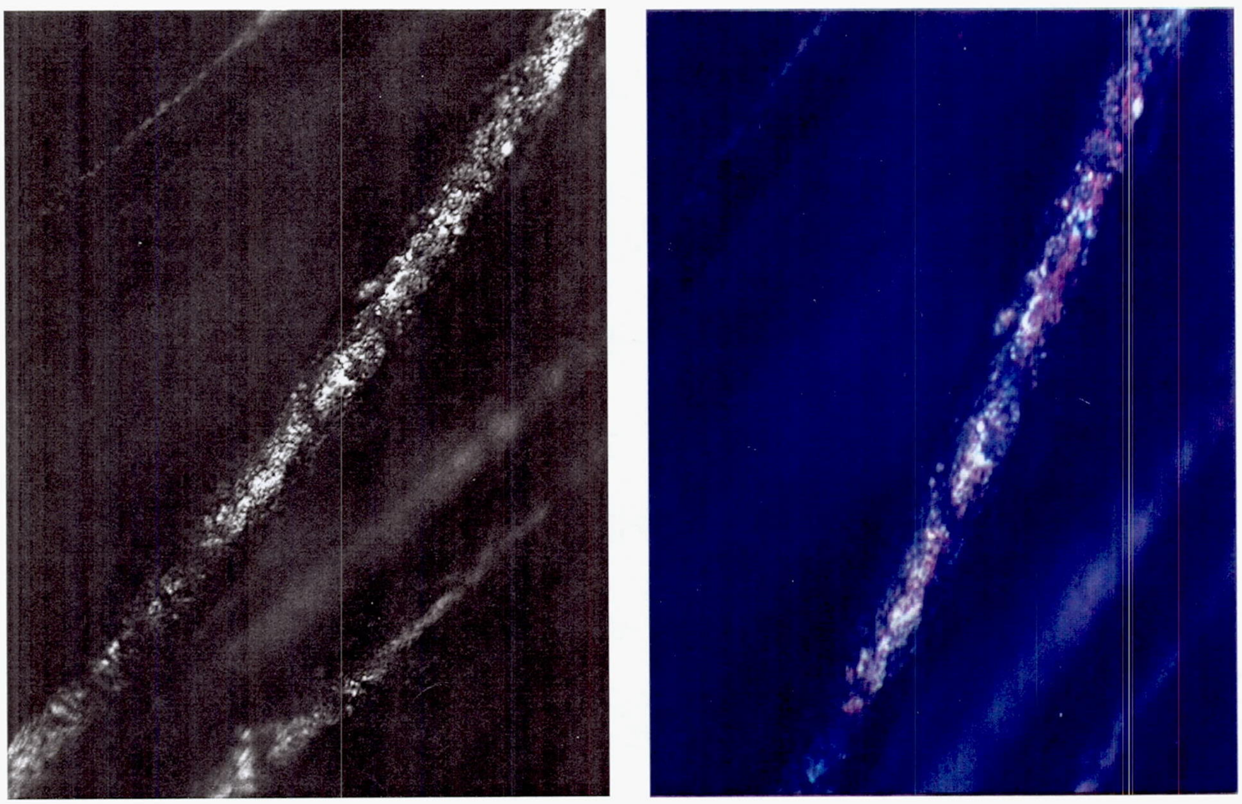


(e) Bristles straight and worn within brush.

Figure 13.—Continued.



(f) "Smearing" of bristle tips.



(g) Oxide scale on bristles.

Figure 13.—Concluded.

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13. ABSTRACT *(Maximum 200 words)*

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